Measurement of the Cosmic Muon Flux at the Stawell Underground Physics Laboratory

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The University of Melbourne

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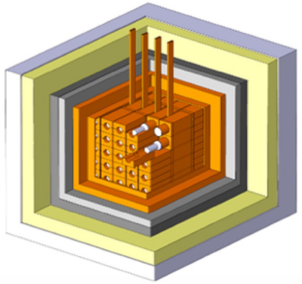
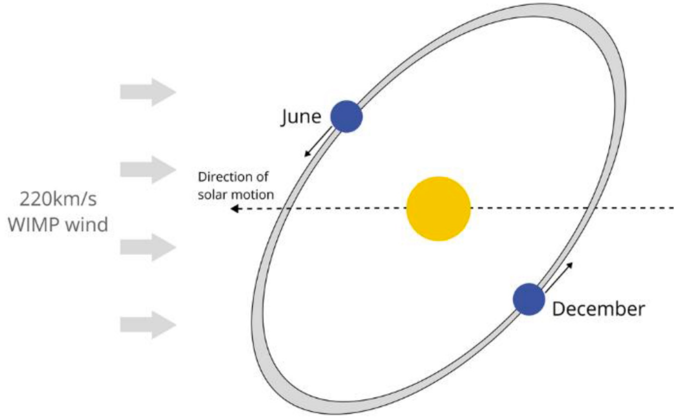
TAUP2025 @Xichang

Dark matter modulation

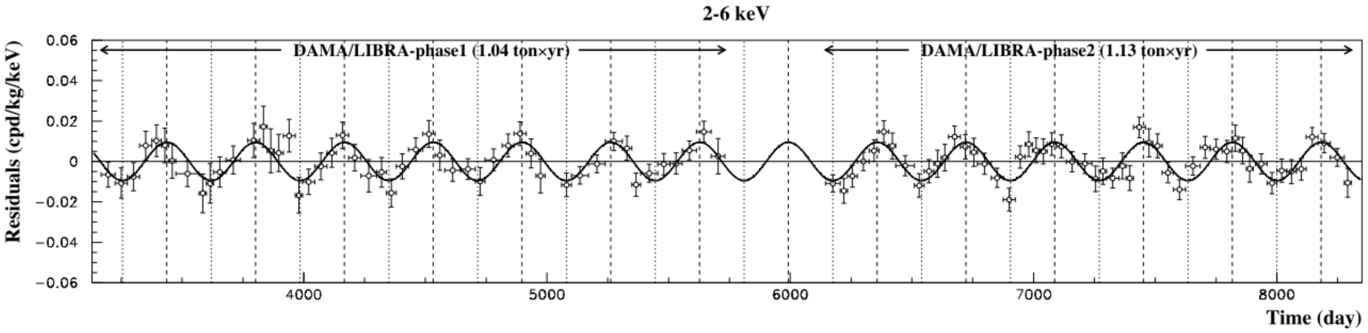
- Annual modulation of dark matter event rate due to the relative motion of the Earth around the Sun in a dark matter halo
- DAMA reports a dark matter annual modulation signal at 13.7σ confidence level in (2-6) keV
  - Amplitude : (0.01014 ± 0.00074)
  - Period: (0.99834 ± 0.00067) yr
  - Phase: (142.4 ± 4.2) days

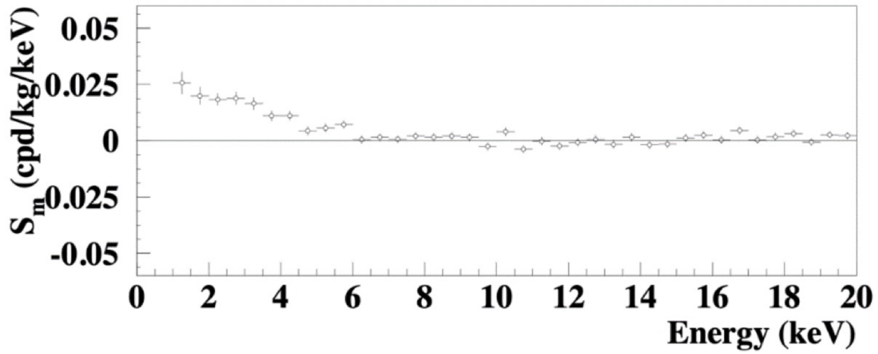
$$S(t) = B + S_0 + S_m \cos(\omega(t - t_0))$$





DAMA/LIBRA set-up





DAMA Collaboration. Nucl. Phys. At. Energy 22 (2021) 329-342

SABRE: a dual site experiment

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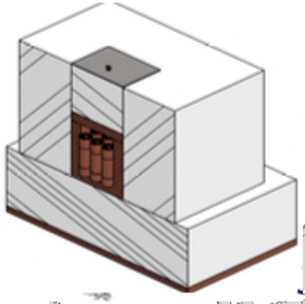
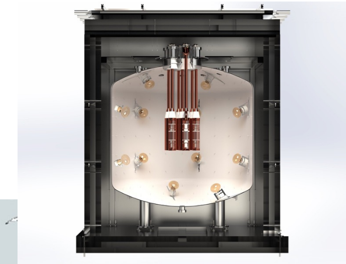
The Sodium Iodide with Active Background REjection (SABRE) experiment foresees two detectors in both hemispheres to disentangle seasonal or site-related effects from the dark matter-like modulated signal

- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy (see Krzysztof Szczepaniec's talk in DM 2A)
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia (see Suerfu's talk in DM 2A)

SAPIENZA UNIVERSITÀ DI ROMA
PRINCETON UNIVERSITY
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEL SALENTO

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso





STAWELL UNDERGROUND PHYSICS LAB

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THE UNIVERSITY OF ADELAIDE
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Australian National University
THE UNIVERSITY OF SYDNEY

SUPL

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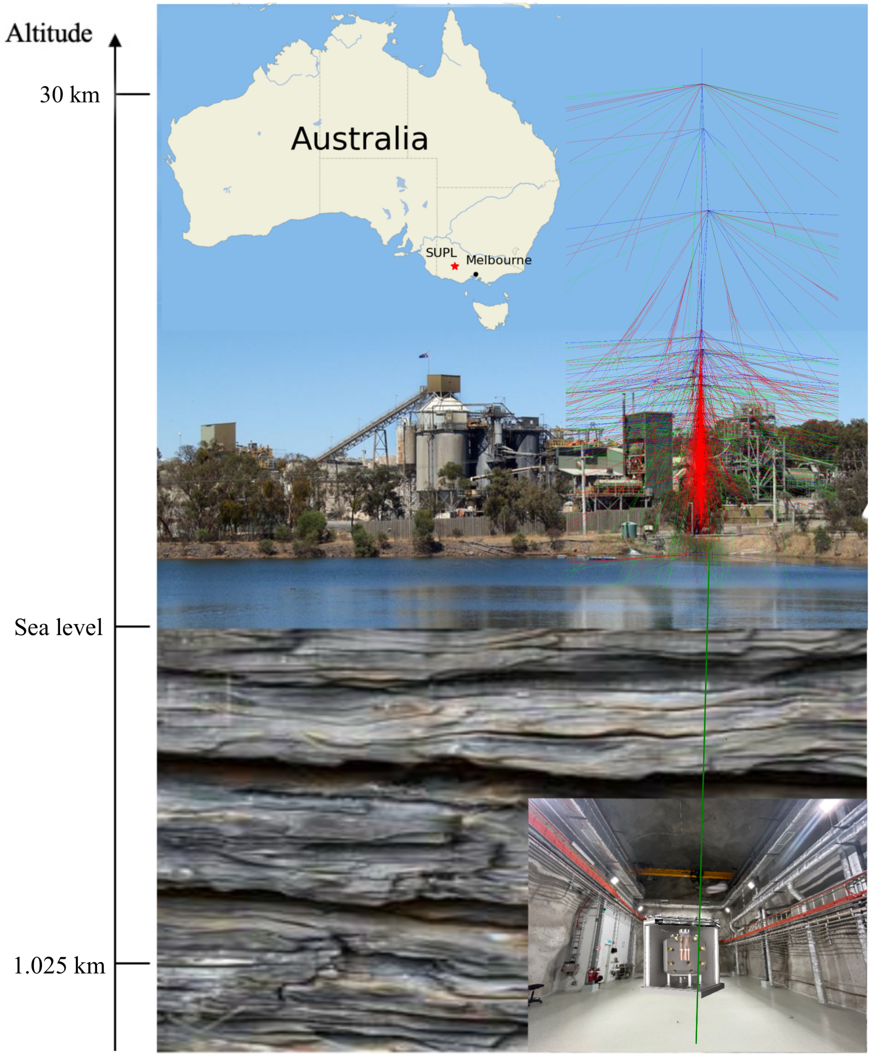


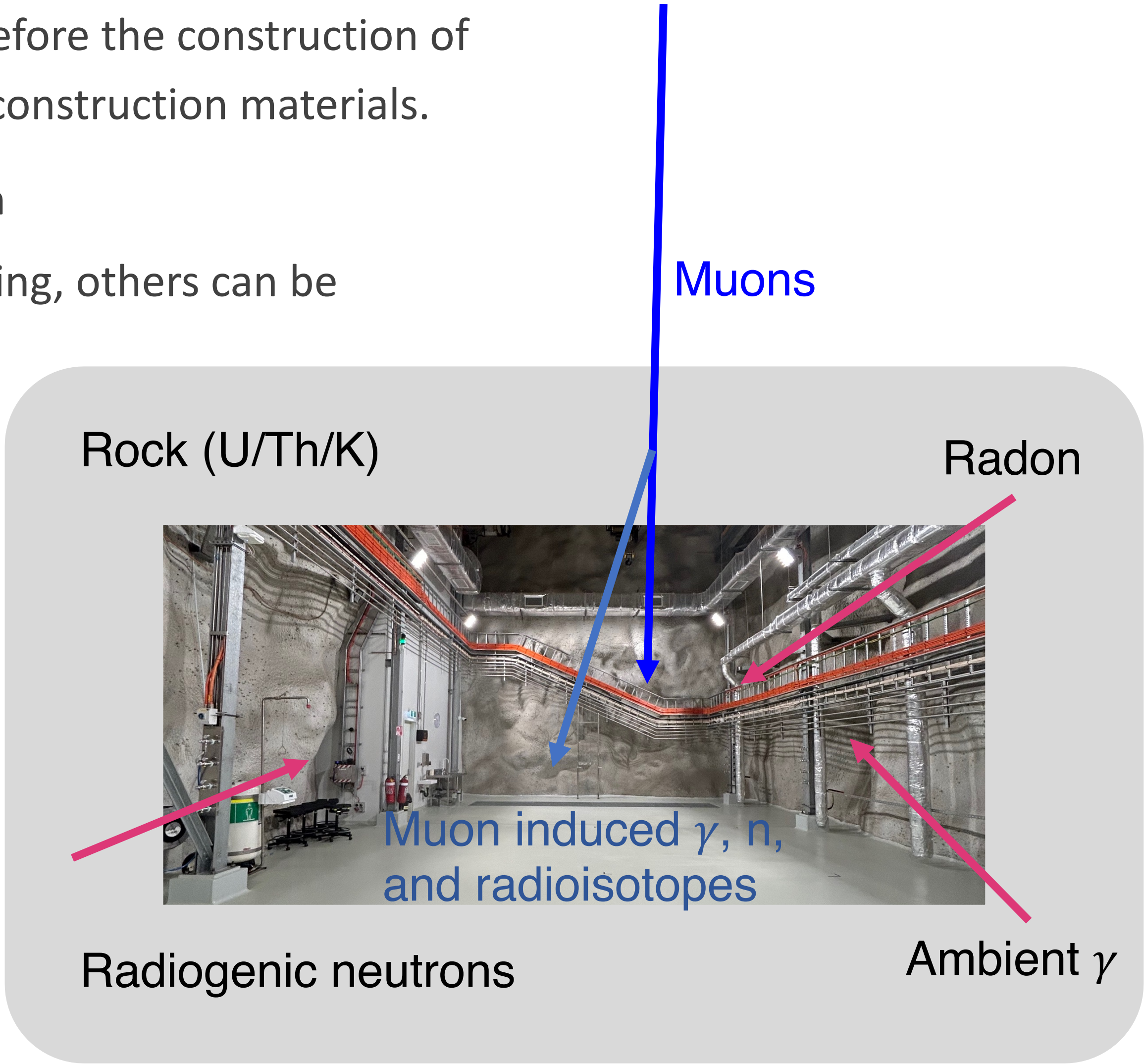
- Stawell Underground Physics Laboratory (SUPL) is the first deep underground laboratory in the Southern Hemisphere. First access in Jan 2024
- SUPL is 240 km northwest of Melbourne
- 1025 m underground, muon flux is attenuated to 10^{-6} of the surface

Background at SUPL

- The neutron and ambient gamma background were measured before the construction of SUPL. Their background will be lower as we use less radioactive construction materials.
- Muon-related and radon backgrounds exhibit annual modulation
- For SABRE South, the muon-induced neutrons are more concerning, others can be suppressed by shielding, air purging, and veto systems.

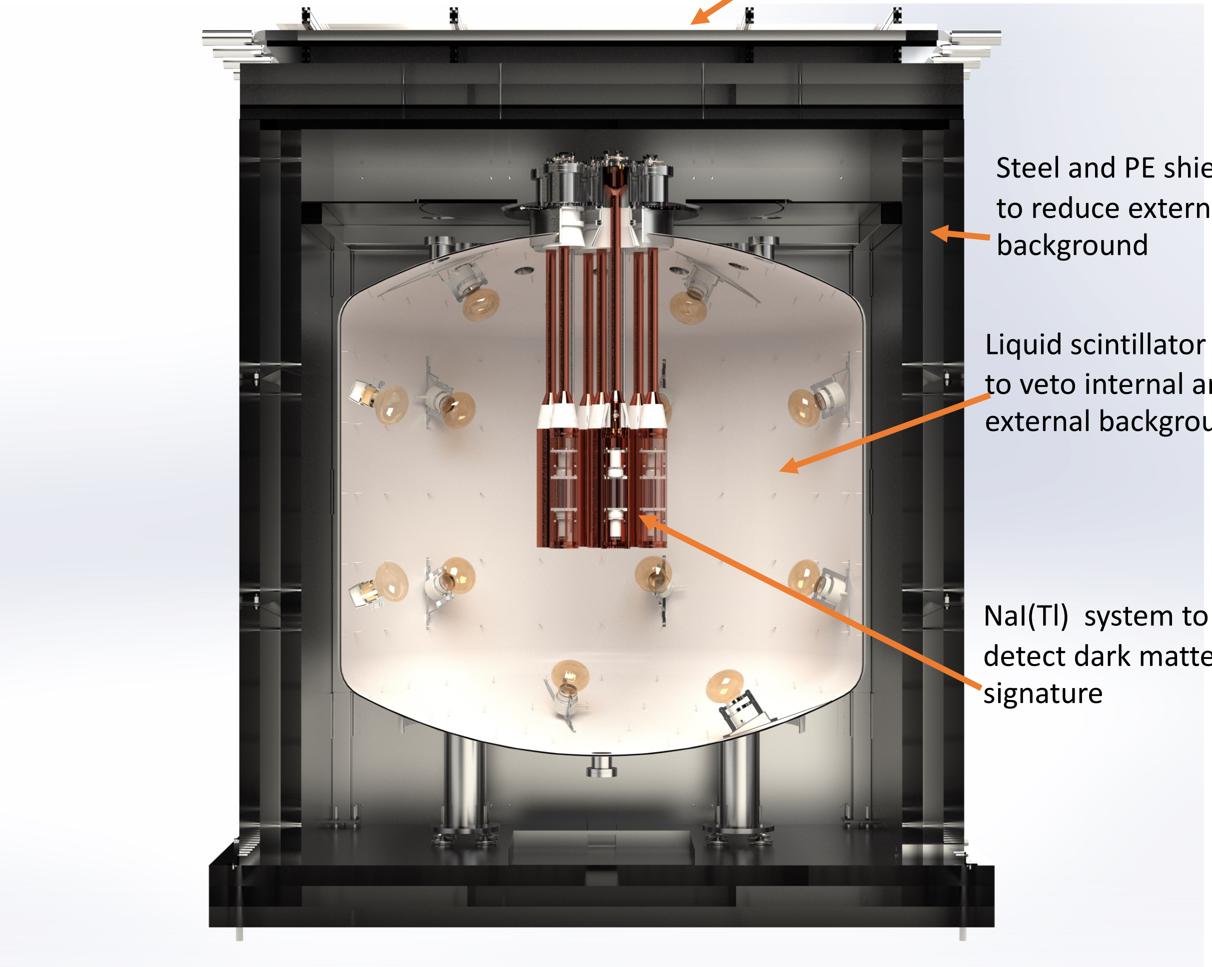
Source	Background	Method
Rock		
Thermal n	3×10^{-5} cm^{-2}s^{-1}	BF$_3$ tube
Fast n	7×10^{-6} cm^{-2}s^{-1}	BF$_3$ tube with $\phi 15''$ HDPE
Natural γ	2.5 cm^{-2}s^{-1}	$3'' \times 3''$ NaI(Tl), Th. 100 keV
Airborne		
Radon	(415±5) Bq m^{-3}	Bertin AlphaE
Muon and muon induced		
Muon	$(5.59 \pm 0.29) \times 10^{-8}$ cm^{-2}s^{-1}	Muon detectors
Muon-induced γ, n and radioisotopes	-	-

Full TDR SABRE South doi.org/10.26188/14618172.v3



SABRE South detector

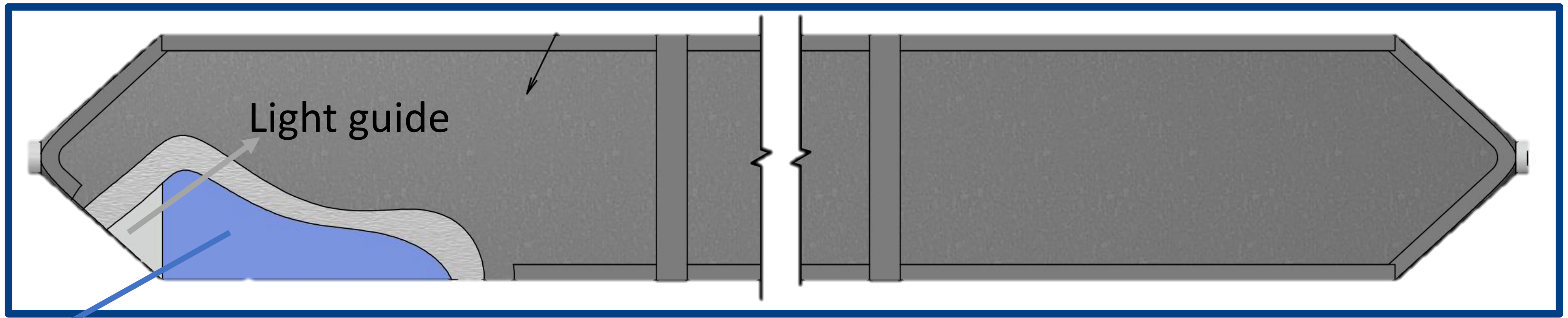
- Muon System
  9.6 m2 x 5 cm EJ200, R13089 PMT x 16 @ 3.2 GS/s
- Passive shielding
  80mm steel + 100mm HDPE + 80mm steel
- Liquid Scintillator Veto System
  12k litres Linear Alkyl Benzene + PPO & Bis-MSB
  Stainless steel, Oil-proof base R5912 PMT x 18(32) @ 500 MS/s (*JINST 20 (2025) 07, P07049*)
- Crystal system
  50 kg of NaI(Tl) Crystals in 7 modules, 1 keV energy threshold, R11065-20 Hamamatsu PMT x 14@ 500 MS/s (*JINST 20 (2025) 07, P07052*)
- Laser and radioactive source calibration systems



Muon detector

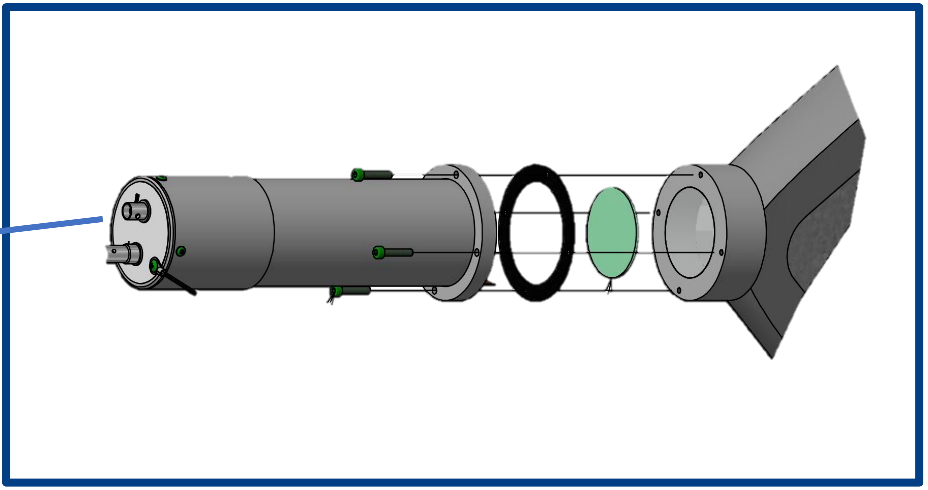
Muon panel

- EJ200 plastic scintillator 300 x 40 x 5 cm^3 (~10 MeV energy deposition)
- Light guide
- Hamamatsu R13089 PMT
- CAEN V1743 digitiser, 3.2 GS/s



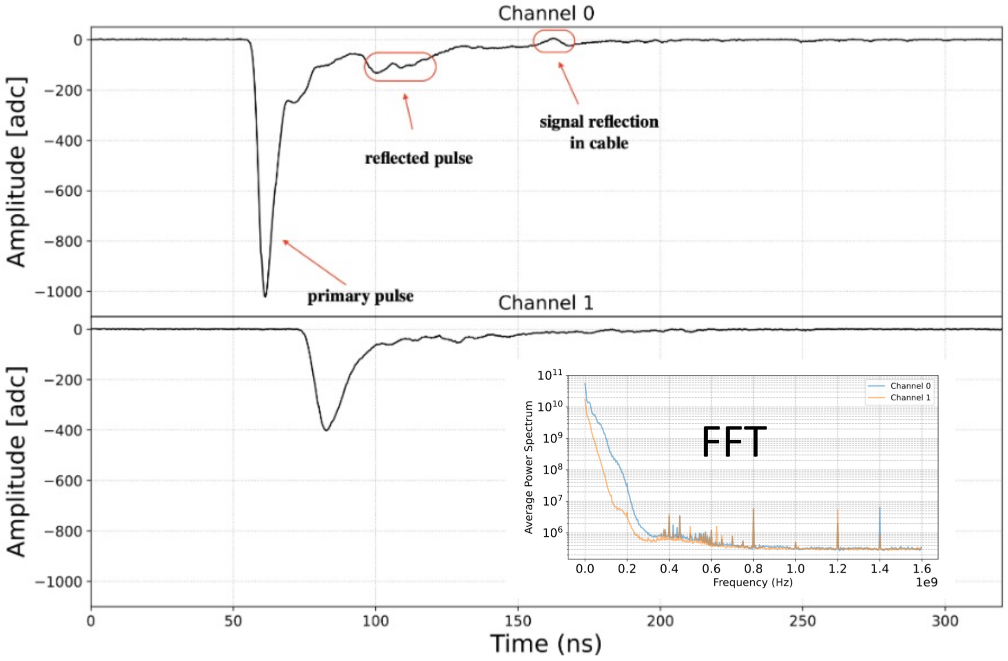
PROPERTIES	EJ-200
Scintillation Efficiency (photons/1 MeV e^-)	10,000
Wavelength of Maximum Emission (nm)	425
Light Attenuation Length (cm)	380
Rise Time (ns)	0.9
Decay Time (ns)	2.1
Pulse Width, FWHM (ns)	2.5
Density (g/cm^3)	1.023
Polymer Base	Polyvinyltoluene
Refractive Index	1.58

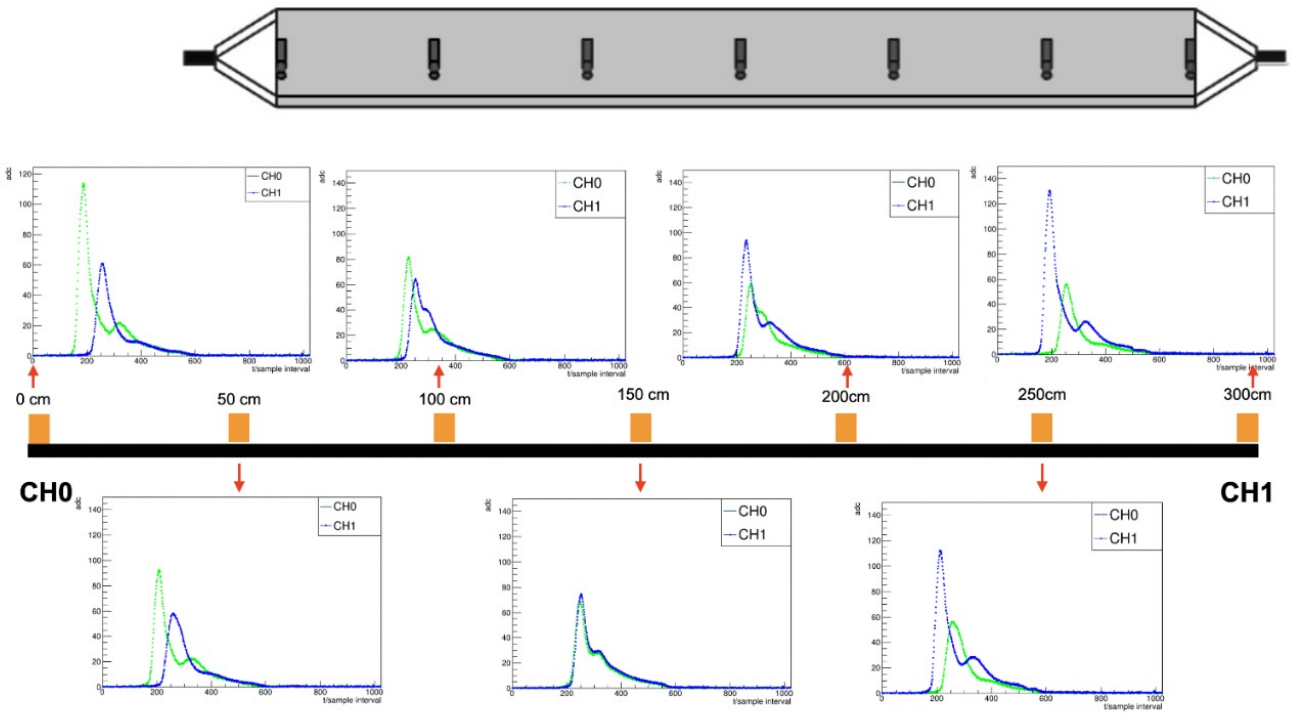
Properties	Hamamatsu R13089
Peak Wavelength (mm)	420
Voltage (V)	1500
Gain	3.2x10^5
Rise Time (ns)	2
Transit Time (ns)	20
Transit Time spread (ns)	0.23
Typical Dark current (nA)	10



Waveform

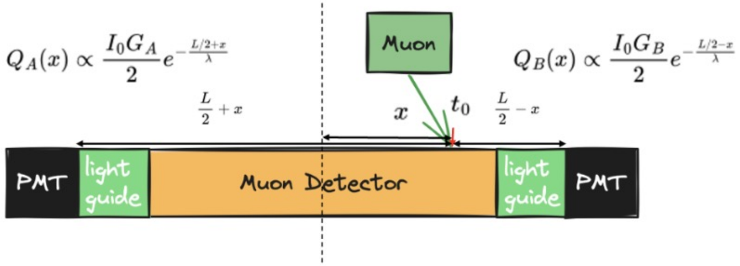
- Reflected pulse piles up on the primary pulse;
- Average waveforms change at different interaction position because of light attenuation;





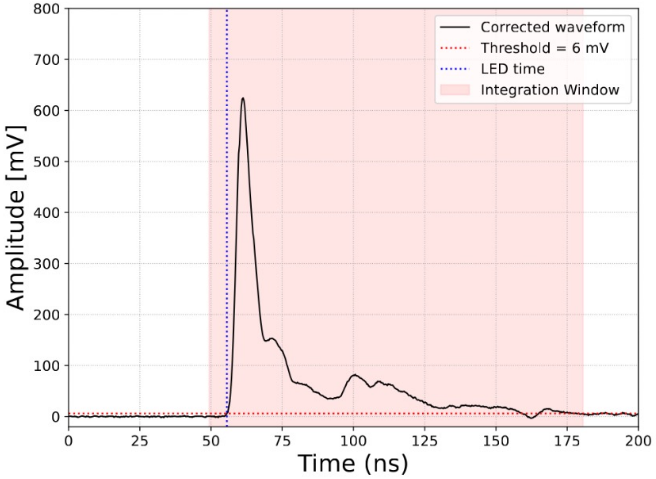
Charge

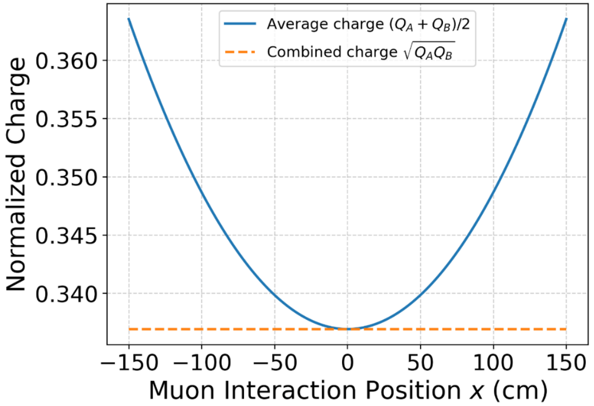
- Charge integration window $[t_{LED} - 20, t_{LED} + 400] \times 0.3125$ ns
- Because of the light attenuation in the scintillator, the charge collected by a PMT is affected by the interaction position;
- Geometric mean charge better reflects the energy deposition in the scintillator

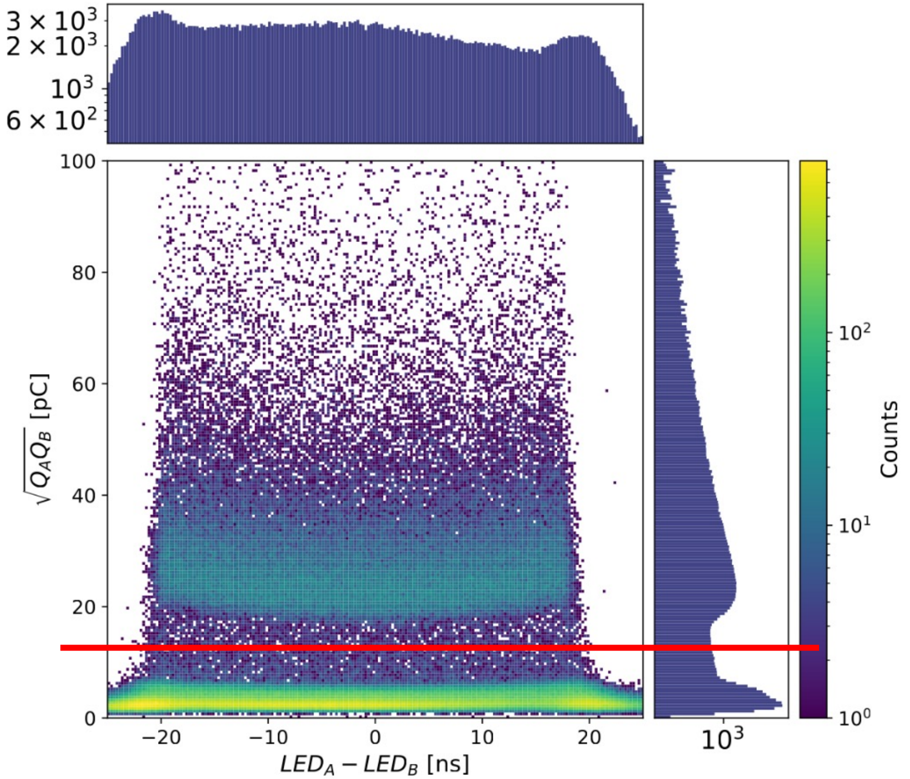


$$Q_{\text{geom}} = \sqrt{Q_A \times Q_B}$$
$$\propto \sqrt{\frac{I_0}{2} e^{-(\frac{L}{2}+x)/\lambda} \times \frac{I_0}{2} e^{-(\frac{L}{2}-x)/\lambda}}$$
$$= \frac{I_0}{2} e^{-\frac{L}{2\lambda}}.$$

$$Q_{\text{arith}} = \frac{Q_A + Q_B}{2}$$
$$\propto \frac{I_0}{4} e^{-(\frac{L}{2}+x)/\lambda} + \frac{I_0}{4} e^{-(\frac{L}{2}-x)/\lambda},$$





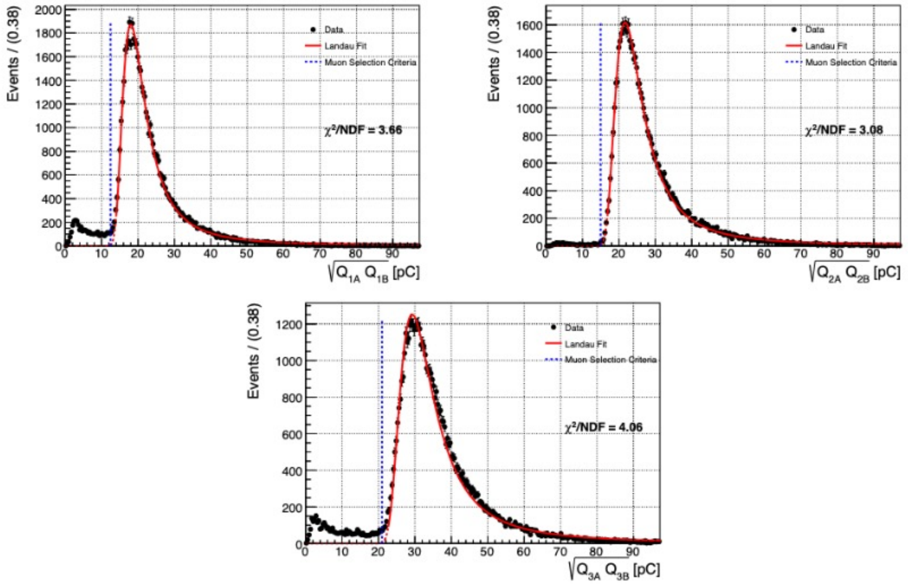


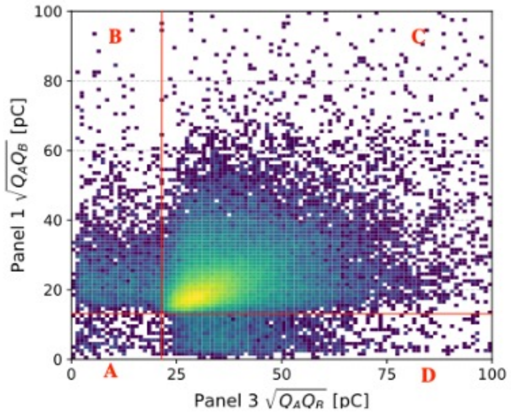
Efficiency

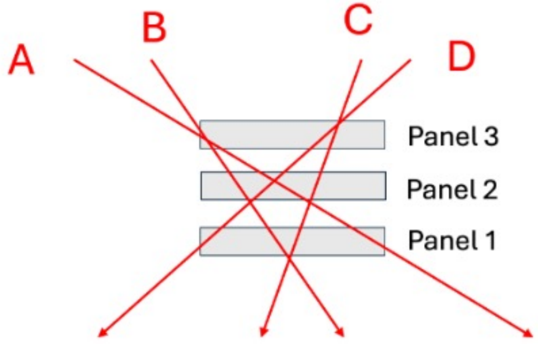
- Three muon panels are stacked to measure the efficiency of the middle panel, pair trigger AND, board trigger OR
- Landau fit to the geometric mean charge, selection criteria at $x_0 - 3\xi$, and altered to estimate the systematic uncertainty
- $N_{123} = 50827$ muons trigger all three panels, $N_{13} = 50531$ muons trigger the top and bottom panel
- Efficiency is calculated by

$$\epsilon_2 = \frac{N_{123}}{N_{13}}.$$

$\varepsilon_{det} = (99.42 \pm 0.03_{stat} \pm 0.23_{syst})\%$

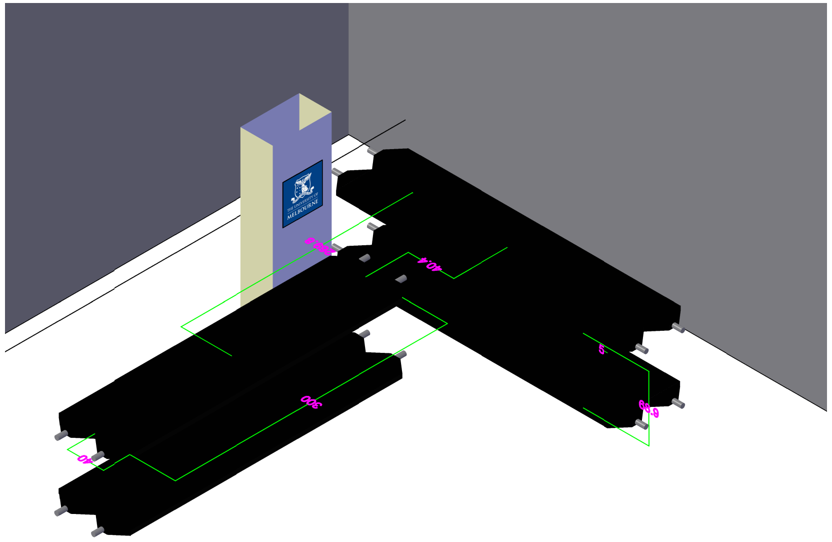


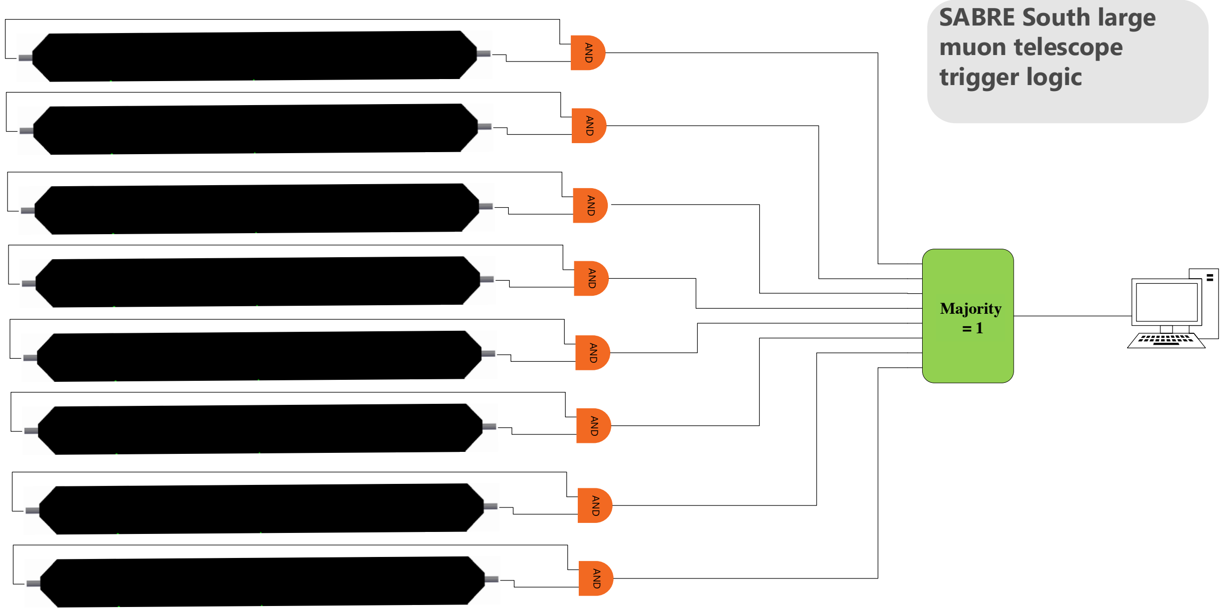


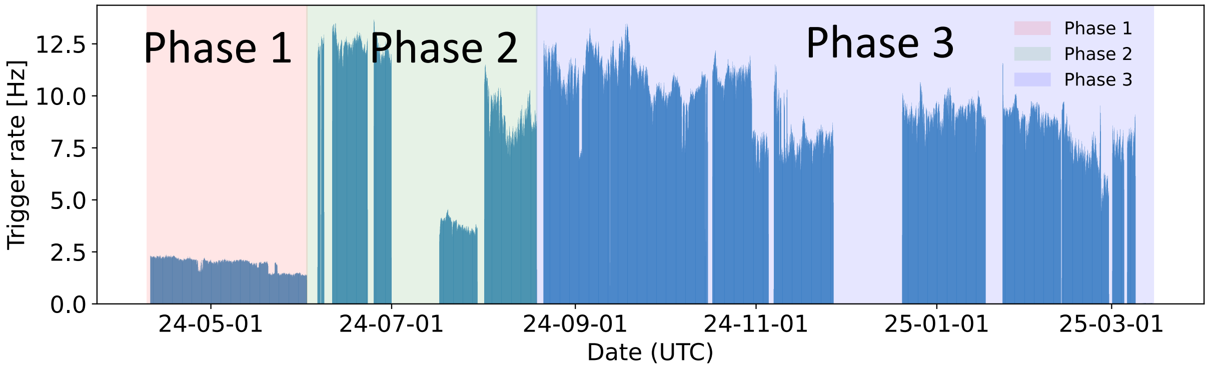


Muon detectors at SUPL

- Muon Detectors running at SUPL since April 2024
- In two telescope configuration
- Aim: to measure muon flux, angular distribution, annual modulation, and test DAQ, data base, data transfer…
- Rate is approximately 120 muons per day

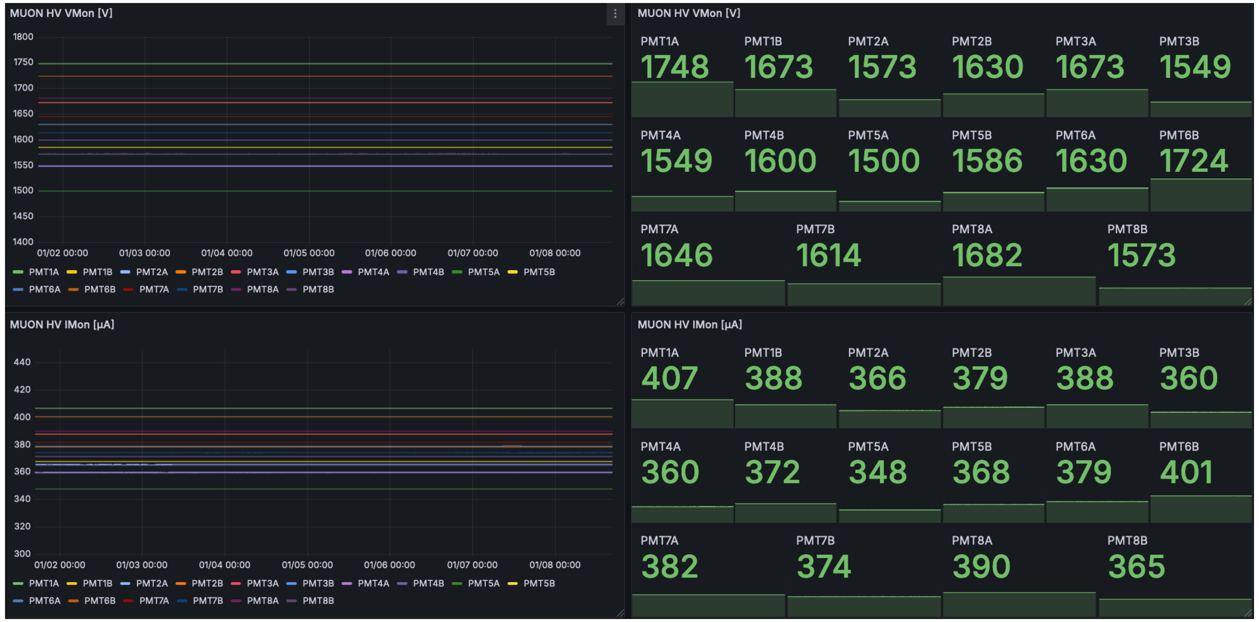


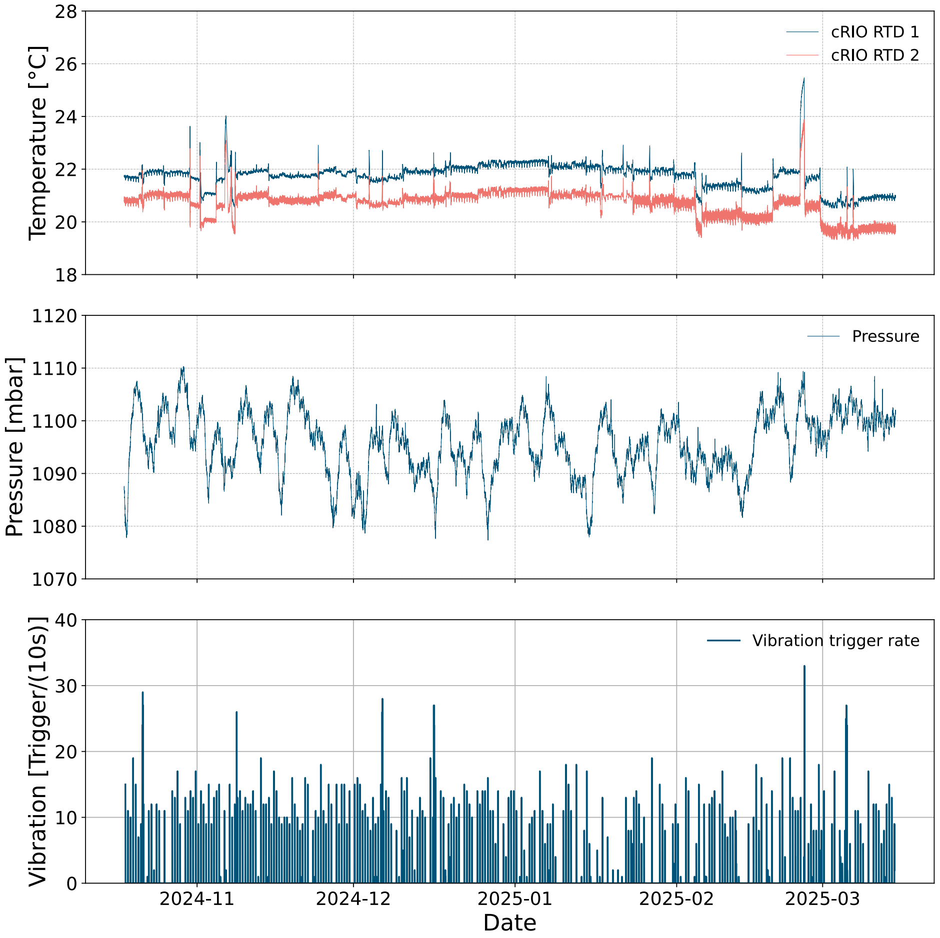




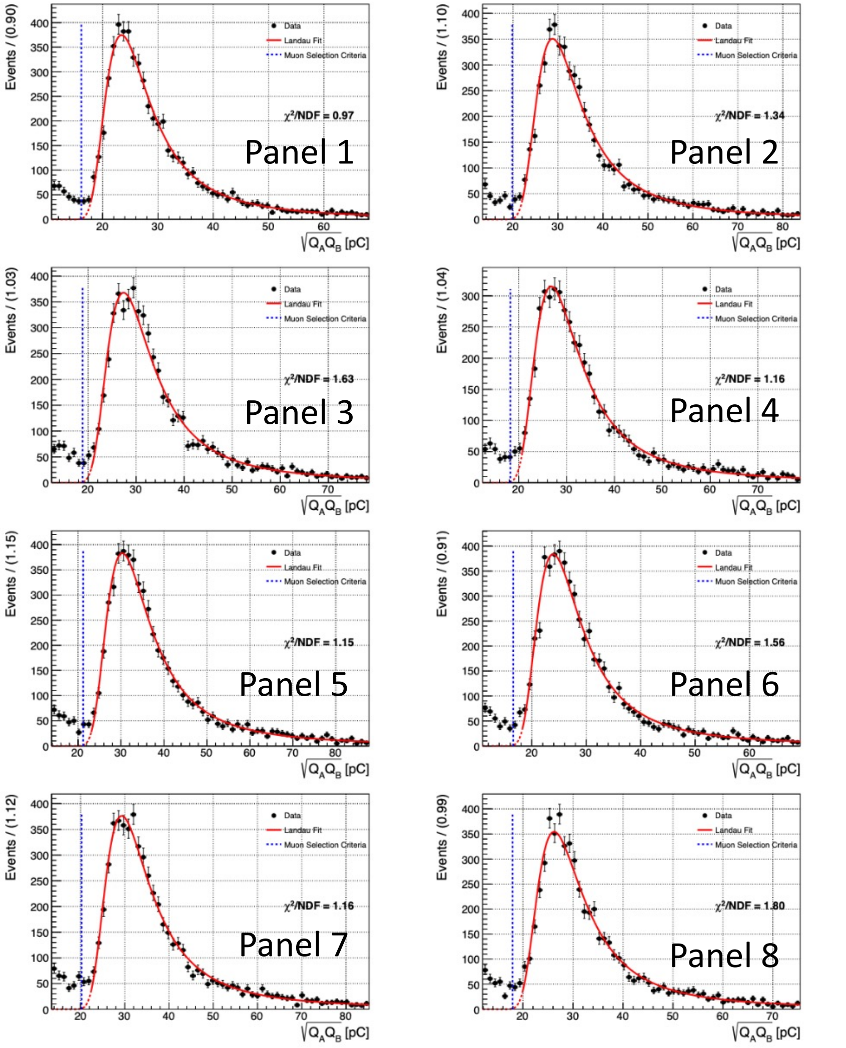
Monitoring

- PMT condition monitored using Grafana
- Temperature is monitored by two precision resistance temperature detectors (RTD) probs with an accuracy of 0.15°C
- Pressure is measured by a Delta Ohm- HD9408.3B piezoresistive sensor with a resolution of 0.1 hPa
- Three accelerometers, to monitor the vibration in three directions

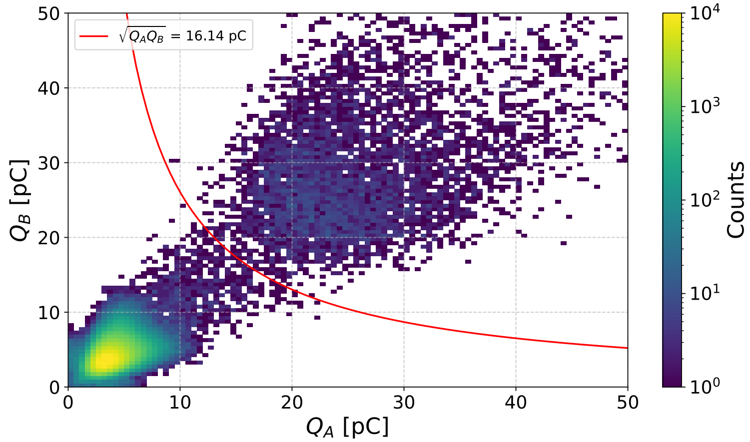


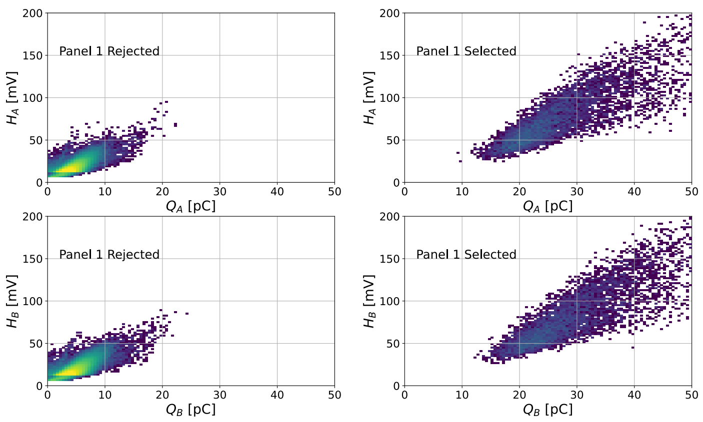


Muon selection criteria



- For each panel, fit the combined charge with a landau distribution, $\mathrm{Landau}(x, x_0, \xi)$
- Select muon events with the geometric mean charge larger than $x_0 - 3\xi$

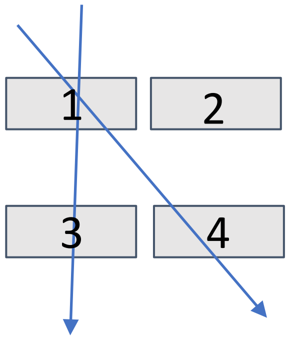


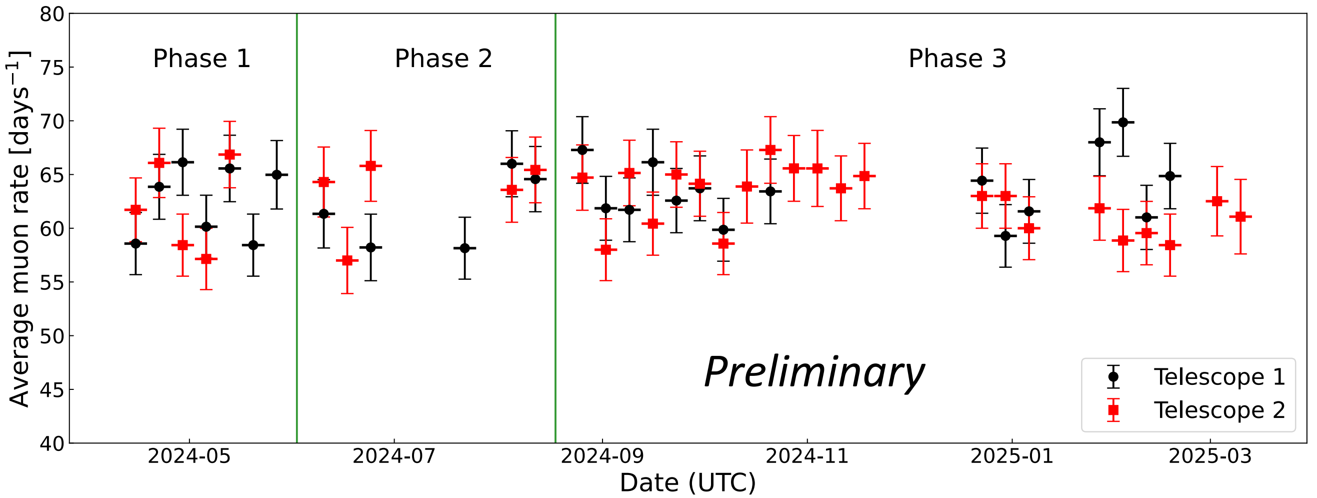


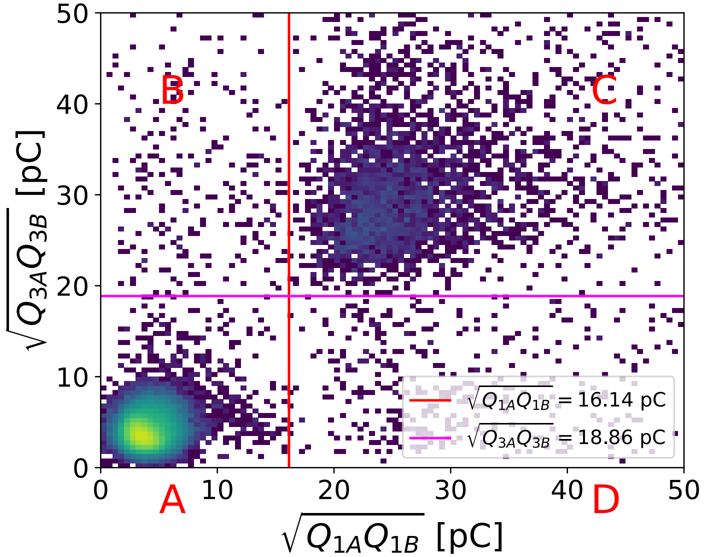
Count muons

For each telescope, we count muons at least passing through a top and a bottom panel

- Telescope 1:
  - Top: panel 1 and 2
  - Bottom: panel 3 and 4
- Telescope 2:
  - Top: panel 5 and 6
  - Bottom: panel 7 and 8



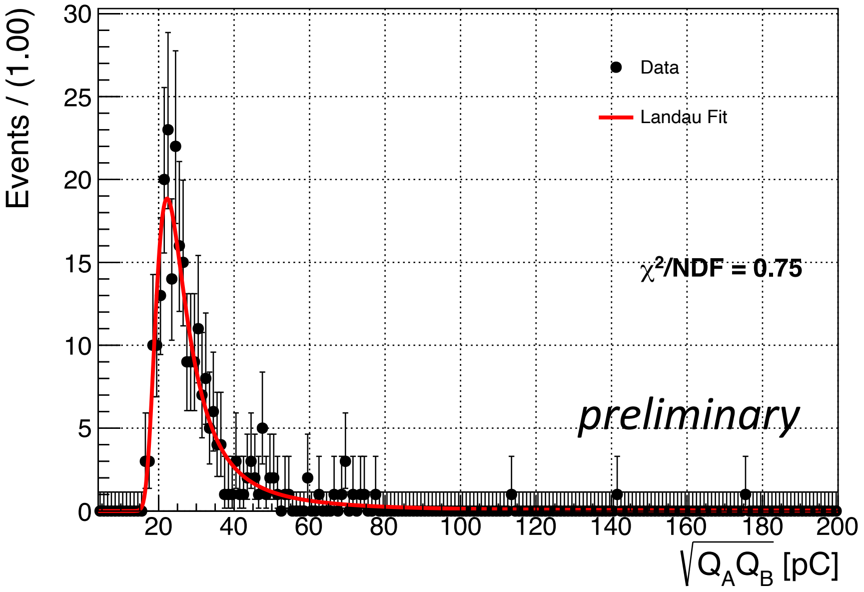




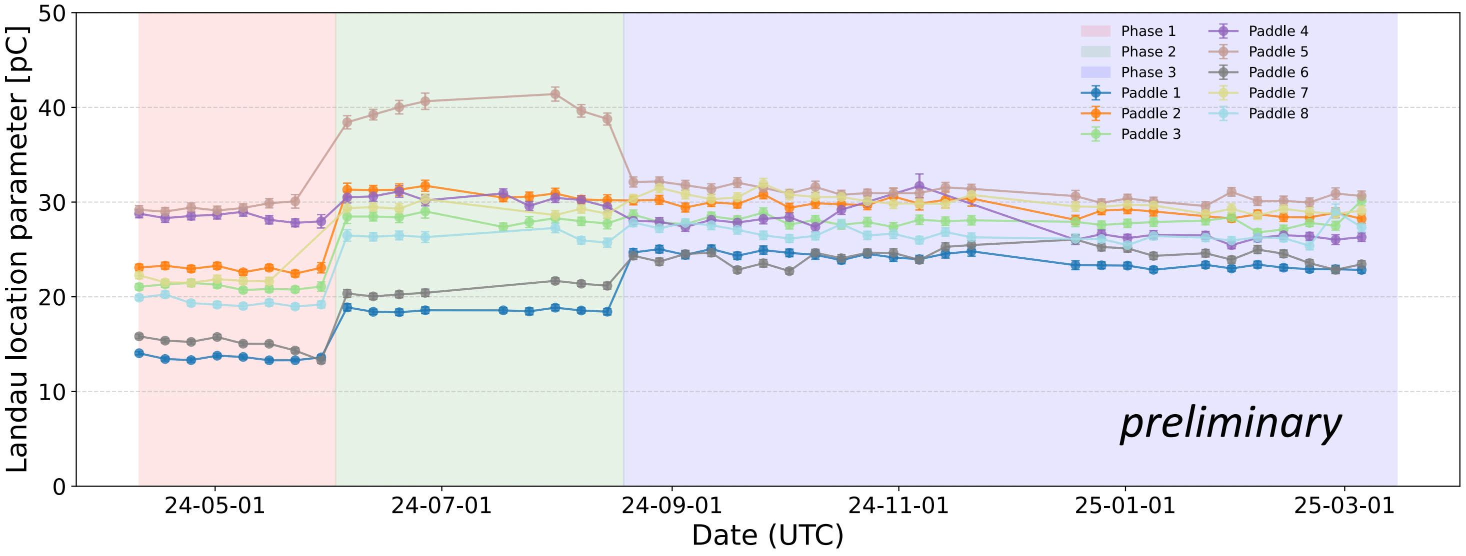
Phase	Telescope 1			Telescope 2		
	Counts	Uptime [d]	Rate [d^{-1}]	Counts	Uptime [d]	Rate [d^{-1}]
Phase 1	3189	51	62.5 ± 1.1	2311	37	62.5 ± 1.3
Phase 2	3000	49	61.2 ± 1.1	2291	36	63.6 ± 1.3
Phase 3	8812	139	63.4 ± 0.7	10079	161	62.5 ± 0.6
Total	15001	239	62.8 ± 0.5	14681	234	62.7 ± 0.5

Gain change

- The location parameter of Landau fit to the muon events is used to monitor the gain change

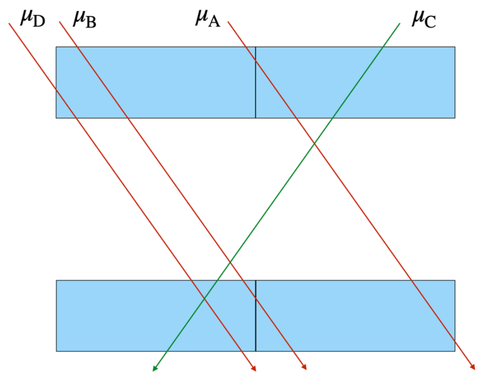


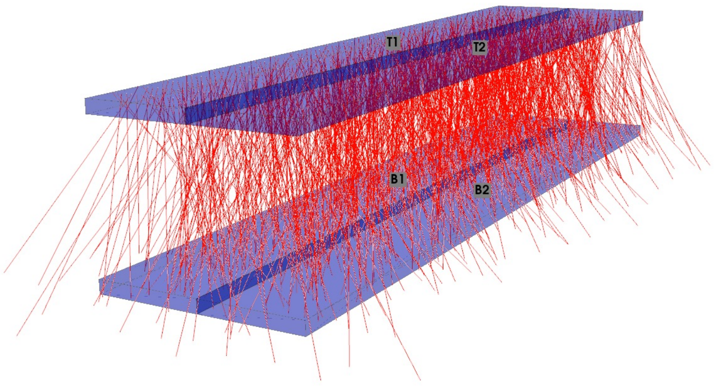
Panel 1, 20250305

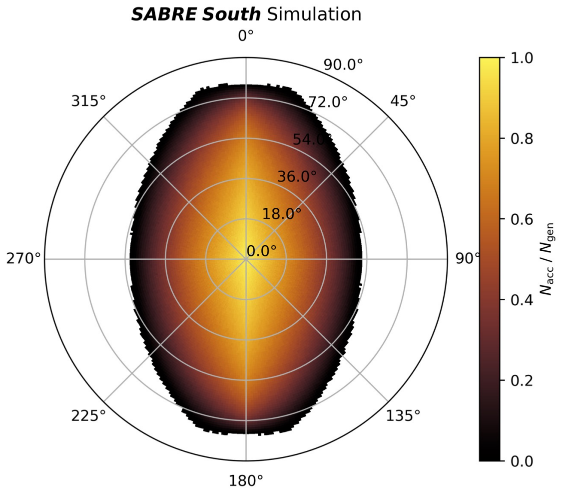


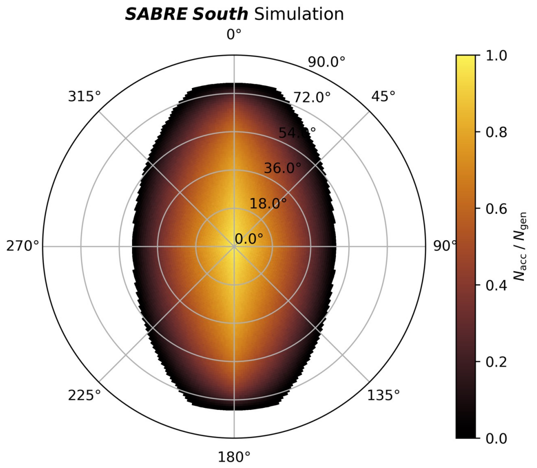
Acceptance simulation

- Detector acceptance modelled with PYRATE (Federico Scutti 2023 *J. Phys.: Conf. Ser.* **2438** 012061)
- Muon events are uniformly and isotropically generated
- Muons passing the edge of the detector are considered for systematic uncertainty









Acceptance simulation

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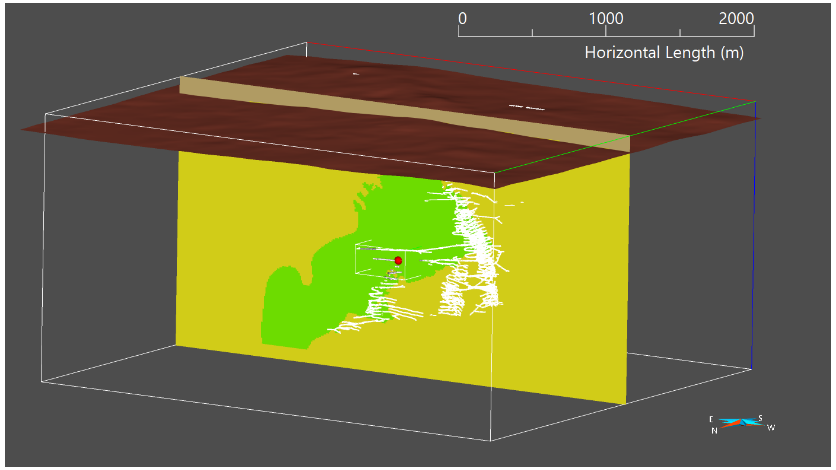
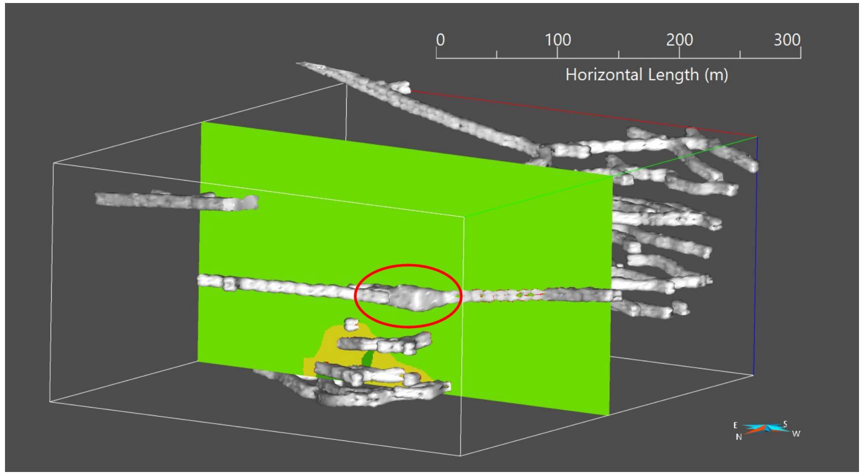
Muon flux simulation

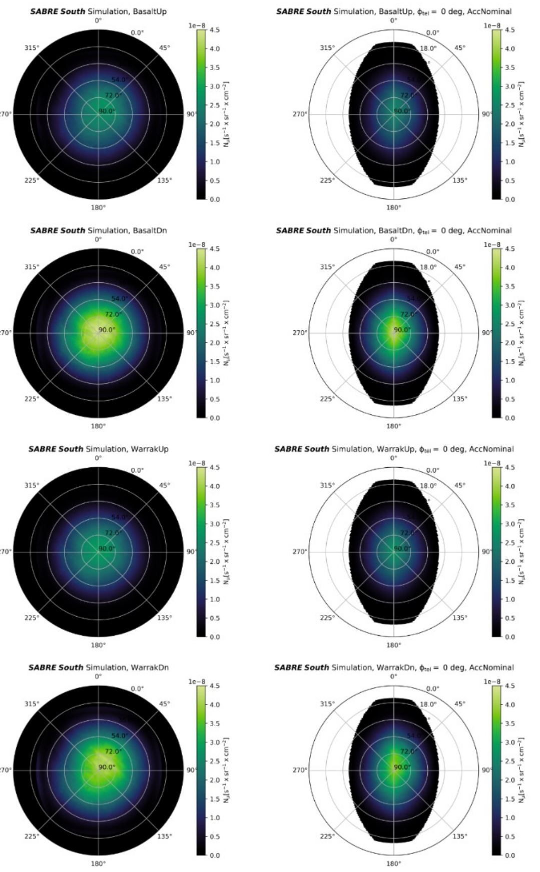
- Use PUMAS (Niess, Comput.Phys.Commun. 279 (2022) 108438) backward propagation of μ from point-like detector
- Muon transport within the voxet model, with many voxels of constant density.
- Surface flux parameterisation from Guan et al (arXiv:1509.06176)
- Geometry and lithology of SUPL are included, basalt $\rho = 2.81 \pm 0.25\ g/cm^3$, sandstone: $\rho = 2.74 \pm 0.3\ g/cm^3$, rock density are altered





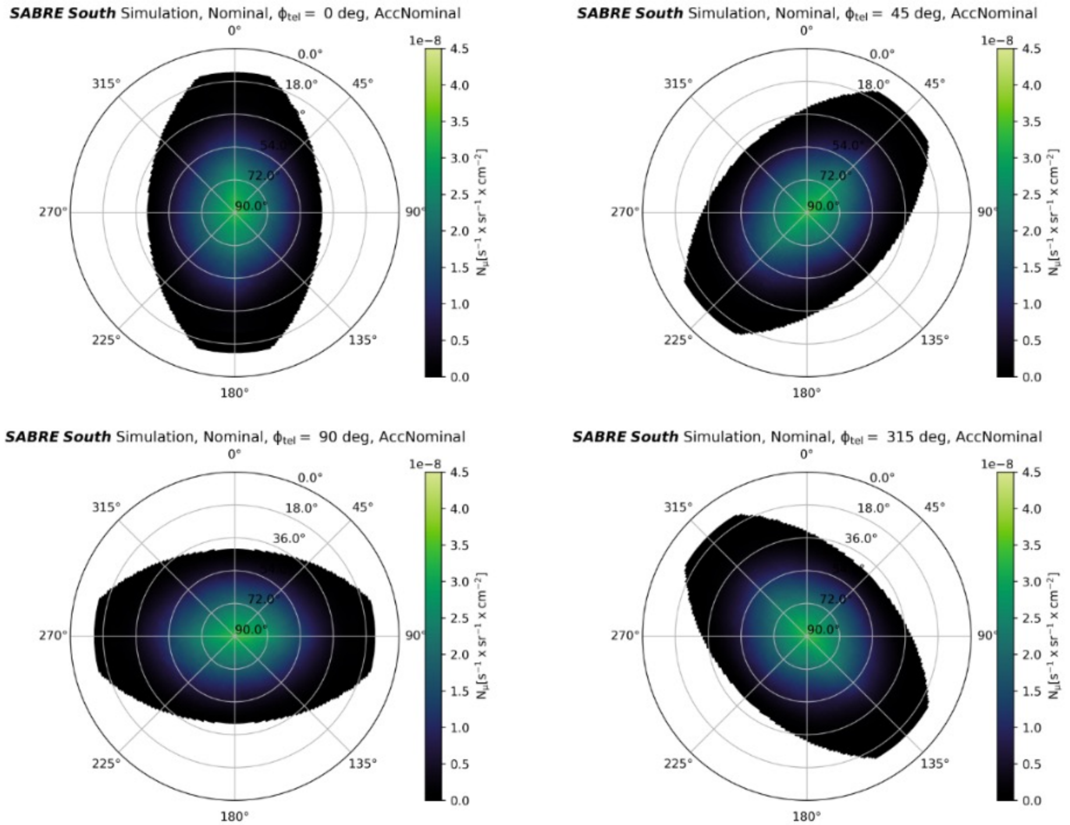
True muon distributoin

With detector acceptance



Acceptance simulation

The orientation of telescopes is altered to estimate the systematic uncertainty



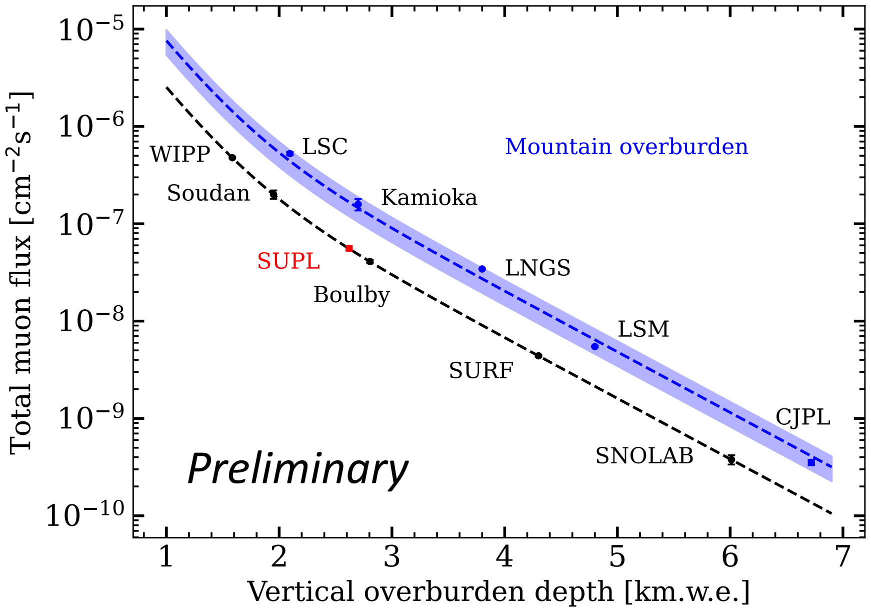
Muon Flux

The muon flux at SUPL is:

$\phi = (5.59 \pm 0.03_{stat} \pm 0.29_{sys}) \times 10^{-8}\ cm^{-2}s^{-1}$

Preliminary

	Nominal value	Uncertainty	
		statistical	systematic
Telescope 1 f^{raw} $[s^{-1} \times cm^{-2}]$	3.03×10^{-8}	$\pm 0.024 \times 10^{-8}$	
Telescope 2 f^{raw} $[s^{-1} \times cm^{-2}]$	3.02×10^{-8}	$\pm 0.024 \times 10^{-8}$	
Average f^{raw} $[s^{-1} \times cm^{-2}]$	3.03×10^{-8}	$\pm 0.017 \times 10^{-8}$	
ε	0.98863	$\pm$ 0.00042	$\pm$ 0.00323
α	0.548		$\pm$ 0.028
f $[s^{-1} \times cm^{-2}]$	5.59×10^{-8}	$\pm 0.03 \times 10^{-8}$	$\pm 0.29 \times 10^{-8}$



Summary

- SUPL is the first deep underground laboratory in the Southern Hemisphere, with access commenced in 2024
- Muon flux has been measured; further data collection is underway for angular distribution, and annual modulation measurement.
- The Software/DAQ/Computing/Database have been tested by the large muon system, and they continue progressing.
- SABRE South commissioning begins this year, clean room and crystal characterisation facilities to be operational soon

SABRE North

INFN LNGS – Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso

INFN – Istituto Nazionale di Fisica Nucleare

Princeton University

Università degli Studi di Milano

Sapienza Università di Roma

Università del Salento

SABRE South

ARC Centre of Excellence for Dark Matter

The University of Adelaide

Swinburne University of Technology

Australian Government

The University of Sydney

Australian National University

The University of Melbourne

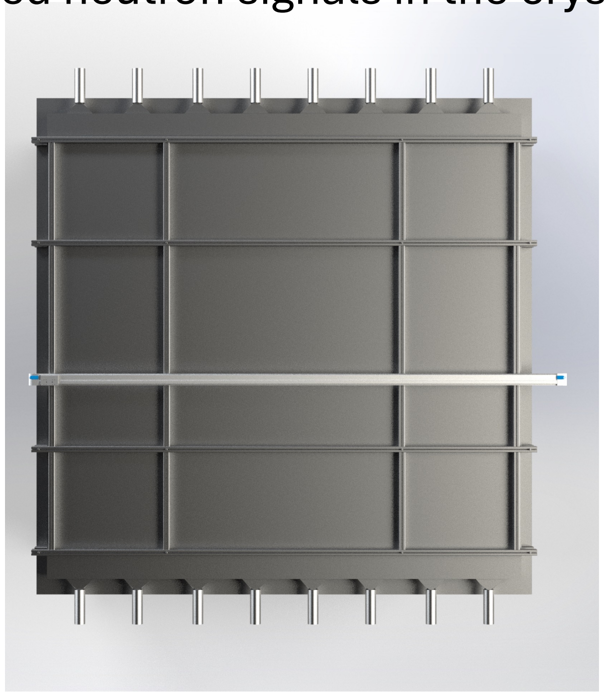
KEK

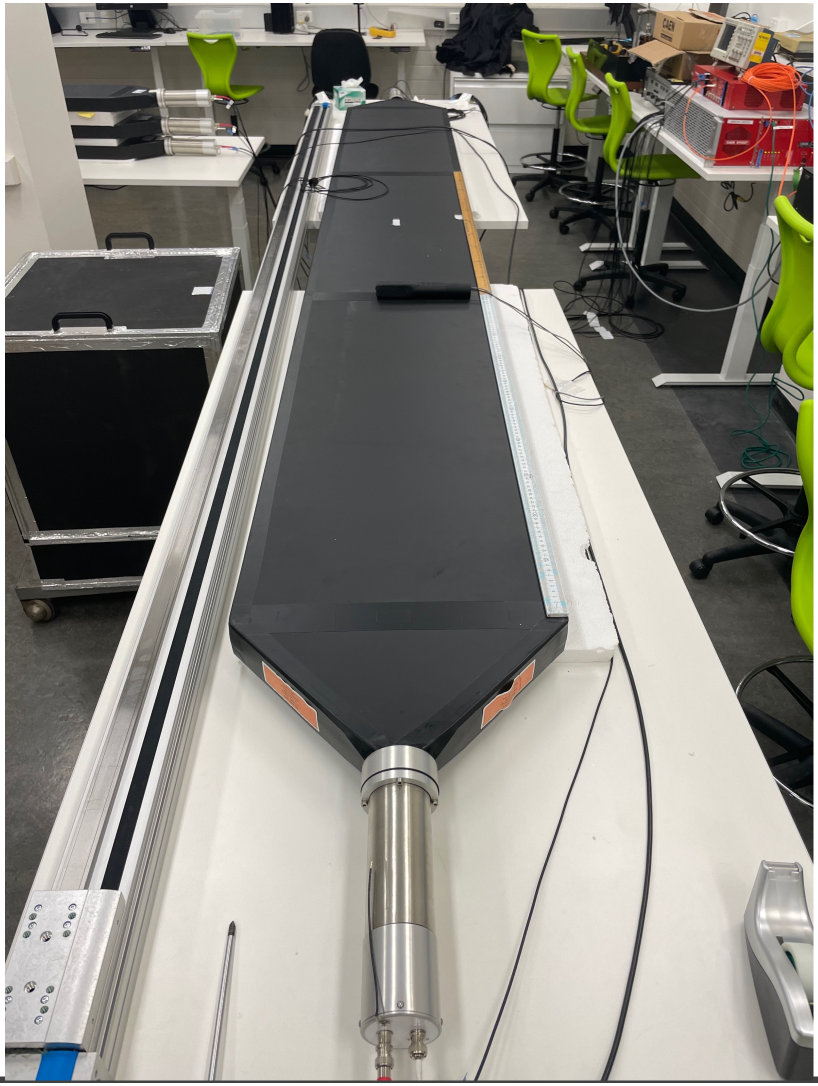
Backup

Muon detector

SABRE South Muon veto system

- 8 muon detector panels with an overall coverage of 9.6 m^2
- Aluminium frame
- Calibration system to move a calibration source over each panel
- Combined with Liquid veto system to reconstruct muon tracks to veto muon induced neutron signals in the crystals

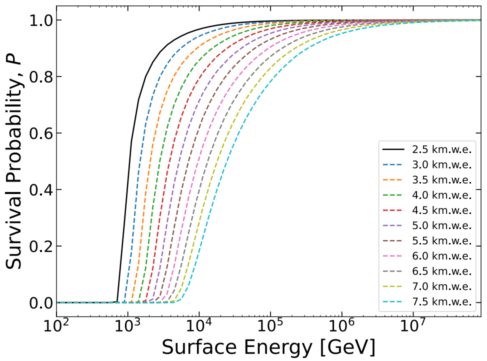


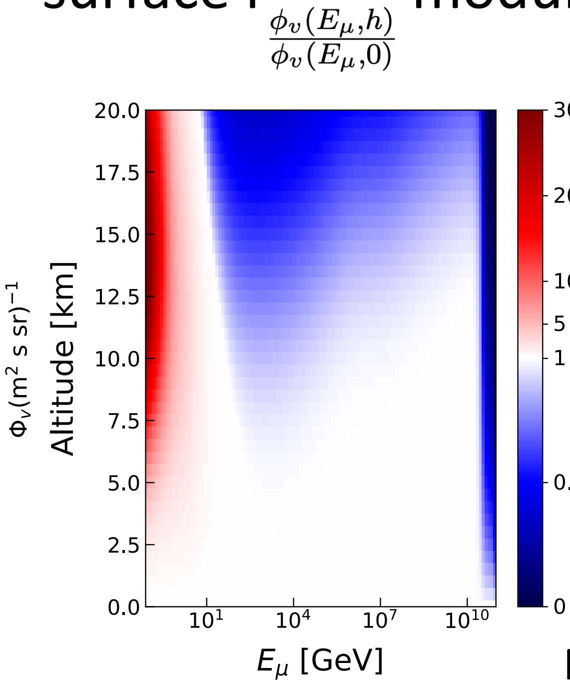


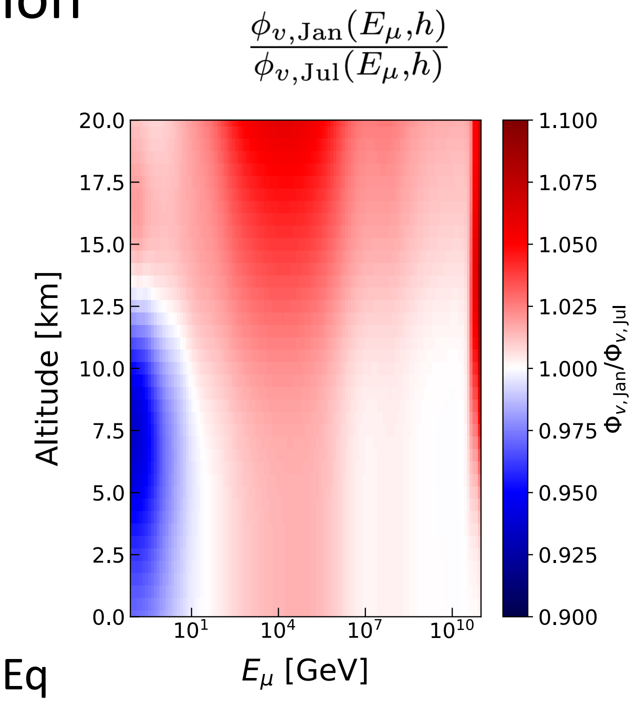
Muon modulation at SUPL

The muon modulation phase in southern hemisphere is different from northern hemisphere

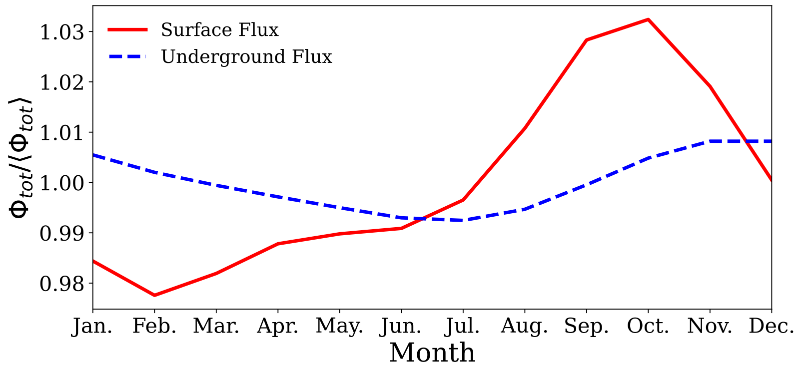
The rock overburden blocks low energy muons, so the phase of underground muon modulation is different from surface muon modulation







MCEq



Using MUTE, the muon annual modulation amplitude is calculated to be 0.79%

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SABRE North and South synergy

SABRE North and South detectors have **common core features**:

- Same crystal production and R&D.
- Same detector module concept (Ultra-pure crystals and HPK R11065 PMTs)
- Common simulation, DAQ and data processing frameworks
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN

SABRE North and South detectors **have different shielding designs:**

- SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS.
- SABRE South will be the first experiment in SUPL, the liquid scintillator will be used for in-situ evaluation and validation of the background in addition to background rejection and particle identification.